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Abstract

We present in this paper a method for evaluating explicitly the contribution of nuclear material accountability upgrades to risk reduction at nuclear facilities. The method yields the same types of values for conditional risk reduction that physical protection and material control upgrades yield. Thereby, potential material accountability upgrades can be evaluated for implementation in the same way that protection and control upgrades are evaluated.

I. Introduction

In order to obtain a quantification of the reduction of risk to nuclear weapons proliferation arising from security upgrades, nuclear materials safeguards specialists have relied on a methodology that derives predominantly from physical protection and material control considerations. This methodology depends on a detailed description of a nuclear facility, the nuclear materials contained therein, physical protection and material control measures to protect them, scenarios by which the materials might be diverted or stolen, and an explicit definition of risk. Within this framework, the reduction in risk arising from specific physical protection and material control upgrades is calculable. Such calculation of risk reduction likely to arise from specific proposed upgrades plays an important role in setting priorities for upgrade implementation and evaluation at various nuclear facilities, both domestic and foreign.

Generally, material accountability measures have played little explicit role in these analyses. Either material accountability is ignored as an element to be treated on another, unexplained plane, or there is an implicit philosophy that if an evaluation for physical protection or material control upgrades warrants them at a specific facility, then concomitant material accountability upgrades are also warranted. This justification leads to acceptable results, but a stronger basis is desirable.

The underlying difficulty is that the separate facets of a multifaceted nuclear safeguards system—physical protection and material control on the one hand, versus material accountability on the other—have different technical objectives. It is therefore understandable that they would not all yield to the same scenarios for risk reduction calculation. In this paper, we present a class of scenarios that permits taking explicit account of material accountability in risk calculations. Thereby the change in risk induced by specific material accountability upgrades can be calculated.

Garcia (2001) has described the analysis of physical protection and material control measures in a comprehensive text, based on experience accumulated by workers at Sandia National Laboratories. The same analysis is used in standard courses given to a wide diversity of practitioners in the security field[2]. From the point of view of this method of analysis, the hazard to nuclear material is theft or sabotage and the desired capability of the security system is to detect and literally neutralize any attempt at theft or sabotage by an outsider or insider adversary -- and by possessing such a capability, ideally to deter any attempt. [Note that the outside adversary – or outsider – may conduct the theft or sabotage in collusion with a member of the facility staff – an insider.]

A nuclear accountability system is not designed to neutralize a threat. It is designed rather to meet two objectives: first, to give accurate, timely, and physically based information about the amount of nuclear material located in a facility; and second, to permit the determination of what material might be missing if there is evidence of theft or other anomalous condition. In both senses material accountability measures complement physical protection and material control measures as part of a multi-faceted safeguards system. It should not be surprising if all three sets of measures do not yield to the same scenarios or the same exact method of analysis for risk reduction.

II. Risk and Risk Reduction Definitions

Evaluation of physical protection, material control, and material accountability upgrades proceeds from the notion that their goal is the reduction of risk resulting from the theft of nuclear weapons and materials. [For the sake of brevity, in the remainder of this paper, we shall not discuss sabotage, which material accountability does not address.] Before describing our proposed use of the risk equation in the context of material accountability upgrades, we need to give a brief overview of how it has been used to evaluate physical protection and material control upgrades in order to understand its usefulness as well as its limitations.

What is the definition of risk? It is a well-defined combination of factors combining the likelihood of detection (and neutralization) of theft and the value of the nuclear material involved. However, the concept of risk developed during the studies of the safety of facilities such as nuclear power plants. For example, Rasmussen, in a study for the U.S. Nuclear Regulatory Commission (U.S. NRC 1974), expressed risk as the probability of the occurrence of an accident and the consequence of the accident

$$R = P_A\, C \qquad (1)$$

Here P_A is the probability of occurrence of the accident and C is consequence of the accident. Failure rates of system components based on experience were used to derive the probability of occurrence of an accident. Failures of components or systems were assumed to be random so that statistical models may be used to calculate the overall probability of failure of entire systems. Also, P_A is assumed to be independent of C.

In an effort to extend this methodology to evaluation of physical protection systems, Bennett, Murphy, and Sherr (U.S. ERDA 1975) modified Rasmussen's formula by adding another variable representing the effectiveness of the physical security system. If P_E denotes the effectiveness of the physical protection system, namely, the probability of the desired security outcome, then $(1- P_E)$ is the probability of system failure. By analogy with Eq. 1, if P_A denotes the probability of the malevolent

[2] E.g., the "Physical Protection Systems Training Course," given by CH2MHill. This course is based on the "International Training Course," that has been given for many years.

action by the adversary and C denotes the consequence of loss of the material, this extension of the Rasmussen methodology leads to the following form of the risk equation frequently used in vulnerability assessments of physical protection and nuclear material control systems:

$$R = P_A\,(1 - P_E)\,C \tag{2}$$

.

The system effectiveness P_E incorporates the probabilities of detection, assessment, interruption, and neutralization (see, e.g., Gardner 1995). The method for determination of these probabilities is well developed for physical protection and material control (Garcia 2001). It is based on an analytical procedure for understanding how physical protection and material control upgrades would likely thwart, or fail to thwart, malevolent adversaries.

However, there have been concerns about the use of Eq. 2 in physical security applications. For example, Richardson (1983) concluded that there were problems with obtaining data for the variables in the equation, with the interdependence of the terms in the equation – especially P_A and C, with the consequence analyses leading to the values of C, and with the assumption that P_A is a random variable. The last of these problems was particularly troublesome, since the Rasmussen methodology had been based on random events of concern to nuclear safety, for example, failure of a core coolant pump at a nuclear reactor. Unlike the failure of a mechanical component, an intentional human action such as a theft attempt cannot be considered random.

The U.S. Department of Energy (DOE) addressed the issue of the probability of an attack by an adversary by instructing that analyses set $P_A = 1$, in other words, basing the risk calculations on the assumption that an attack will occur. Consequence values were set between zero and one, "intuitively" correlating graded safeguards with consequences. For example, theft of an assembled nuclear weapon has a consequence value of 1.0, theft of a Category 1 quantity of an oxide or carbide has a consequence value of 0.7, and theft of a Category 4 quantity of nuclear material has a consequence value of 0.1. The modified version of Eq. 2 then yields the *conditional risk* (once again, see Gardner 1995)

$$R = (1 - P_E)\,C \tag{3}$$

This simplified version of the Rasmussen methodology does not address all of the concerns that have been expressed in connection with employing a methodology developed for probabilistic component failures in the context of nuclear material safeguards. However, used with appropriate cautions regarding the limits of applicability, it has provided an intuitive and common sense methodology for comparative evaluations of physical protection and material control systems.

For a situation where one is comparing the relative effectiveness of different nuclear safeguards measures for specified targets of theft at a particular facility, the value of the consequence C will not change. What changes is the value of the probability, which would increase if safeguards measures were upgraded. Thus, the change in risk, ΔR, given upgraded safeguards measures is

$$\Delta R = R_e - R_u = [\,(1 - P_e) - (1 - P_u)]\,C = (P_u - P_e)\,C \tag{4}$$

Here R_e and P_e refer to the existing safeguards system and R_u and P_u refer to the upgraded system. (To avoid a multiplicity of subscripts, the subscript "E" used in Eqs. 2 and 3 is omitted in Eq. 4.) We may use Eq. 4 to evaluate potential upgrades for their likely contribution to risk reduction. Alternatively, we may use Eq. 4 to evaluate implemented upgrades for their actual contribution to risk reduction. In either case, the change in risk calculated by using Eq. 4 is a change in *conditional risk.*

For material accountability, we expect that in Eq. 3 the system effectiveness will incorporate the probability of detection, specifically, the detection of theft of nuclear material. Regulations specifying the effectiveness of material accountability measures have been expressed probabilistically, for example, as the basis for analyses of the effectiveness of the verification work of the International Atomic Energy Agency (under the rubric "Diversion Path Analysis" and “Safeguards Effectiveness Assessment Methodology”; see, e.g., Glancy and Kull 1979 and Keisch and Sanborn 1984). In domestic safeguards, regulatory documents specify performance requirements for material control and accountability (MC&A) elements probabilistically, for example, sampling for physical inventories must be able to detect a 3% defect for category I nuclear materials with a confidence level of 95% (U.S. DOE 2000)

Others have addressed the concern of quantitatively assessing the effectiveness of material accountability upgrades at a nuclear facility in different ways. For example, Arkhangelsky and coworkers (1997) showed that for a system of accountable items, the information entropy –a concept employed in information theory – will decrease as a result of physical inventories and inspections, thus allowing a quantitative assessment of the effect of inventories and inspections. Shultz (2002), noting the insufficient emphasis on the role of MC&A in the protection of nuclear material from theft or diversion, has made suggestions on expanding the role of MC&A in the vulnerability assessment process, specifically by adopting an MC&A module in the ASSESS software that is frequently used in such vulnerability assessments. However, neither of these papers specifically considers the effectiveness of MC&A upgrades in terms of the reduction of risk.

III. Application to Material Accountability

For material accountability measures, the technical objectives are first, to give accurate, timely, and physically based information about the amount of nuclear material located in a facility, and second, to permit the determination of what material might be missing if there is evidence of theft. Thus, the provision of information about the material in the facility is both for routine reporting and for determining what is missing in the event of an actual theft. Note that “timely” has somewhat different meanings in international and domestic safeguards. In traditional international safeguards, the nuclear material theft scenarios involve the nation-state and the nuclear facility operator. The timeliness of the information is intended to detect theft before the material can be converted into nuclear weapons. In domestic safeguards, the nuclear material theft scenarios involve an insider, possibly in collusion with an outside adversary; the nation-state in this case is attempting to prevent the theft of the material.. In the case of domestic safeguards, the timeliness of the information is intended to detect theft as soon as possible after it occurs to promote recovery.

For the purposes of analysis and to distinguish among the various possible material accountability measures, it is useful to assume that the material is indeed missing and that the adversary has employed certain concealment measures to hide the action and thereby delay detection. In a typical regulatory or international inspection situation (e.g. Glancy and Kull 1979 and Keisch and Sanborn 1984), various verification measures are studied against combinations of theft (understood as a diversion in the international case) and concealment actions to find a satisfactory set of verification measures that has such a high probability to detect the theft that it will be detected or that the adversary will be deterred from attempting it.

The material accountability measures under consideration here proceed from a base case of bookkeeping only. The potential upgrades and the base case are as follows, with each succeeding measure encompassing the preceding ones:

i. Bookkeeping only; no physical inventory taking (PIT) even for items;
ii. Doing a 100% PIT of items without measurement;
iii. Weighing a statistical sample of the items;
iv. Weighing and gross gamma ray measurement for a statistical sample of the items; and
v. Weighing and gross gamma ray and neutron measurement for a statistical sample of the items

Now we proceed to illustrate the method for a three theft scenarios:

Scenario 1: Theft of Whole Items Without Replacement

Scenario 2: Theft of Whole Items With Concealment by Replacing the Real Items with Inert Items of Equal Weight and with Seals Bypassed

Scenario 3: Theft of Whole Items With Concealment by Replacing the Real Items With Gamma-Emitting Radioactive Material of Equal Weight and with Seals Bypassed

For these scenarios we give in tabular form the results of the calculations of risk and risk reduction. There are two tables for each scenario: first, a table with symbolic expressions for the results of interest; and second, a table with numerical results based on assumed parameters. We first present the meaning of the symbols.

Legend for tables

a. β is the non-detection probability required for the verification measures; in the simplest interpretation, it covers random sampling alone. What is very important is that β is generally specified by regulation.

b. P_d is the probability of detection for the original or upgraded material accountability measure, which encompasses both sampling and (by assumption here) 100% effective measurement.

c. C is the consequence value for the nuclear material, chosen here as 0.8 to correspond to Category 1 quantities of so-called "pure products" – special nuclear materials in metallic form that are relatively easily converted into weapons.

d. R is the risk associated with the loss of the nuclear material.

e. ΔR is the risk reduction induced by the upgraded material accountability measure with respect to the original measure for that scenario.

Scenario 1: Theft of Whole Items Without Replacement

(a) Symbolic Version

Material Accountability Measures	P_d	$R=(1-P_d)\ C$	ΔR
Bookkeeping only; no PIT even for items	0.0	C	--
Identifying 100% of the item inventory	1.0	0.0	C
Weighing a statistical sample of the items	$1-\beta$	βC	$C(1-\beta)$
Weighing and gross gamma ray measurement for a statistical sample of the items	$1-\beta$	βC	$C(1-\beta)$

(b) Numerical Version

Material Accountability System Measures	Detection Probability $P_d = 1-\beta$	Consequence C (=0.8)	Risk $(1-P_d)$ C	Risk Reduction $\Delta R= (P_e-P_u)$ C
Bookkeeping only; no PIT even for items	0	0.8	0.8	--
Identifying 100% of the item inventory	1	0.8	0	0.8
Weighing a statistical sample of the items (β=0.5)	0.5	0.8	0.4	0.4
Weighing and gross gamma ray measurement for a statistical sample of the items (β=0.5)	0.5	0.8	0.4	0.4

Scenario 2: Theft of Whole Items With Concealment by Replacing the Real Items with Inert Items of Equal Weight and with Seals Bypassed

(a) Symbolic Version

Material Accountability Measures	P_d	$R=(1-P_d)\ C$	ΔR
Bookkeeping only; no PIT even for items	0.0	C	--
Identifying 100% of the item inventory	0.0	C	0
Weighing a statistical sample of the items	0.0	C	0
Weighing and gross gamma ray measurement for a statistical sample of the items	$1-\beta$	βC	$C(1-\beta)$

(b) Numerical Version

Material Accountability System Measures	Detection Probability $P_d = 1-\beta$	Consequence C (=0.8)	Risk $(1-P_d)$ C	Risk Reduction $\Delta R = (P_e - P_u)$ C
Bookkeeping only; no PIT even for items	0	0.8	0.8	--
Identifying 100% of the item inventory	0	0.8	0.8	0
Weighing a statistical sample of the items (β=0.5)	0	0.8	0.8	0
Weighing and gross gamma ray measurement for a statistical sample of the items (β=0.5)	0.5	0.8	0.4	0.4

Scenario 3: Theft of Whole Items With Concealment by Replacing the Real Items With Gamma-Emitting Radioactive Material of Equal Weight and with Seals Bypassed

(a) Symbolic Version

Material Accountability Measures	P_d	$R=(1-P_d)$ C	ΔR
Bookkeeping only; no PIT even for items	0.0	C	--
Identifying 100% of the item inventory	0.0	C	0
Weighing a statistical sample of the items	0.0	C	0
Weighing and gross gamma ray measurement for a statistical sample of the items	0.0	C	0
Weighing and gross gamma ray and neutron measurement for a statistical sample of the items	$1-\beta$	βC	$C(1-\beta)$

(b) Numerical Version

Material Accountability System Measures	Detection Probability $P_d = 1-\beta$	Consequence C (=0.8)	Risk $(1-P_d)$ C	Risk Reduction $\Delta R = (P_e - P_u)$ C
Bookkeeping only; no PIT even for items	0	0.8	0.8	--
Identifying 100% of the item inventory	0	0.8	0.8	0
Weighing a statistical sample of the items (β=0.5)	0	0.8	0.8	0
Weighing and gross gamma ray measurement for a statistical sample of the items (β=0.5)	0	0.8	0.8	0
Weighing and gross gamma ray and neutron measurement for a statistical sample of the items (β=0.5)	0.5	0.8	0.4	0.4

IV. Discussion

These tables present a simple set of scenarios that illustrate how material accountability upgrades can be evaluated in the same framework that is used to evaluate physical protection and material control upgrades. The illustrations yield a quantitative value of risk reduction for the simplest material accountability upgrade measure—performing an item inventory—as well as for more refined material accountability measures. Of course the particular risk reduction values obtained depend on the parameters used in the calculations. In this sense, one particular virtue of this material accountability evaluation is that the detection probability is typically specified by regulation. Thus the safeguards measures employed will be chosen to meet the required detection probability.

Undeniably the theft and concealment scenarios illustrated here derive from earlier work more appropriate to the international situation, where the threat is the nation-state itself and the significant resources it can mobilize (e.g. Glancy and Kull 1979 and Keisch and Sanborn 1984.)

These calculations by no means exhaust the possibilities for material accountability measures that can be employed to upgrade a safeguards system. In general, they would be chosen on the basis of their contribution to providing the desired information and to allowing the necessary discrimination among theft scenarios. For example, in the case of a chemical process where nuclear material changes compound or form, measurement uncertainties become a more important issue.

V. Conclusion

There are some basic distinctions among physical protection, material control, and material accountability. A key goal of physical protection measures is the actual neutralization of an attempted theft or sabotage of nuclear material, in particular by violent outsiders. In this sense, physical protection is an immediate safeguards measure. The goal of nuclear material control measures is similar to that of physical protection measures, except that they are focused on insiders. For both of these kinds of measures, there is a well-developed and practiced methodology for calculating their probability of success in thwarting theft or sabotage of the nuclear material. Given a value for the nuclear material, these probabilities lead to a value of risk. Upgraded physical protection and material control measures, by decreasing the risk, thereby lead to risk reduction.

In contrast, the goal of material accountability is to provide a determination at a particular time of the amount of nuclear material present in a given material balance area. Primarily, therefore, material accountability measures would serve the objective of confirming amounts on a measured basis. They are generally not designed to, and do not, thwart malevolent actions; however, they could detect protracted theft before "completion" if the measures are sufficiently sensitive. But if a theft does occur, then the role of material accountability is late detection.

Independent of the scenario by which a theft occurs, material accountability measures can be interpreted probabilistically, and thereby they also lead to a direct description in terms of risk. What is required is a set of theft and concealment scenarios to which the material accountability measures apply differently. For a given scenario of theft and concealment, variations in risk depend both on the material accountability measures implemented (the rows in the Section III tables) and on the concealment methods, if any, employed by the adversary (the different Section III tables).

Detection probabilities for the accountability measures are typically specified by regulation, while consequence values span a relative range and derive from expert judgment. The risk values obtained are therefore relative as well as conditional, since they depend on the unknown probability of adversary action, here and generally assumed to be unity.

In summary, on the basis of probabilistic descriptions, both physical protection and material control measures on the one hand, and material accountability measures on the other, fit into a risk calculation that permits a risk reduction value to be assigned to physical protection, material control, and material accountability upgrades. An obvious extension of this method of analysis would be to posit sets of possible upgrades, determine the costs and benefits (risk reduction) of each set, and finally recommend a set to implement based on the costs, benefits, resource constraints, and mandated or desired outcome.

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